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**Introduction**

Starting in FY16, projects that conduct cryogenic test activities in the Industrial Building 1 Test Facility will be invoiced for the cost of cryogenics, a consumable that is by far the largest M&S expense for operating the facility. This note summarizes the accounting model for assessing those costs to projects, and presents the cost basis for charges in FY16 and FY17.

**IB1 Cryogen Use and Cost History**

Cryogen use in IB1 has been tracked and studied for many years to try to minimize costs. Detailed records of Nitrogen and Helium consumption exist and provide a reliable basis for predicting future use. Here we present how those cryogenics are used, establish what the typical annual consumption of these cryogenics is in the IB1 facility, and indicate expectations for any changes in the near future. Cost trends and near future expectations will also be discussed.

Helium is the working refrigerant in a closed system that includes the cryogenic plant (compressors and cold box) with gas and liquid storage tanks, pipes for delivering/recovering the helium to/from test stand cryogenic vessels, and sub-atmospheric pumping systems used to lower temperatures below 4 Kelvin. Although it is a closed system, there are losses, and helium is purchased to replace the lost inventory. Helium leaks are distributed around the facility and are difficult to find (some are known but difficult to repair). Helium usage (what we must purchase to maintain helium inventory in the system) is carefully monitored, and when evidence appears of increased use, labor is spent to search for new leaks. There are also some losses due to necessary "pump & helium back-fill" purification steps to prevent air contamination that can disrupt performance of the helium system; in the absence of "full stream purification", helium gas used in this process is vented to atmosphere. A full stream purification upgrade is approaching completion, and is expected to begin operation at the start of FY17, which will result in reduction of lost helium and improved plant reliability.

Nitrogen is purchased in liquid form (LN<sub>2</sub>) and is not re-used; it's a low-cost way to increase efficiency of the helium system. LN<sub>2</sub> is primarily used to pre-cool helium in the cold box as part of the helium liquifaction process, but also in purifiers to remove contaminants, and in thermal shields that reduce heat load to the liquid helium around the entire facility.

Historic data show that average rate at which Nitrogen and Helium are consumed is pretty consistent from year to year. There have been periods where use has been either elevated or reduced, generally for known reasons. Figure 1 shows the recent history of helium use (what is added to the plant

inventory), monthly for the past 6 fiscal years. FY15 use was anomalously high due to two large helium leaks that had developed and were eventually found and stopped in late June. FY16 use was anomalously low because helium purchases were suspended prior to plant maintenance that included a full storage dewar warmup (this was a rare occurrence needed for system upgrades), to ensure all helium could be captured in our gas storage tanks. The slope of helium consumption in normal use is consistent from year to year.

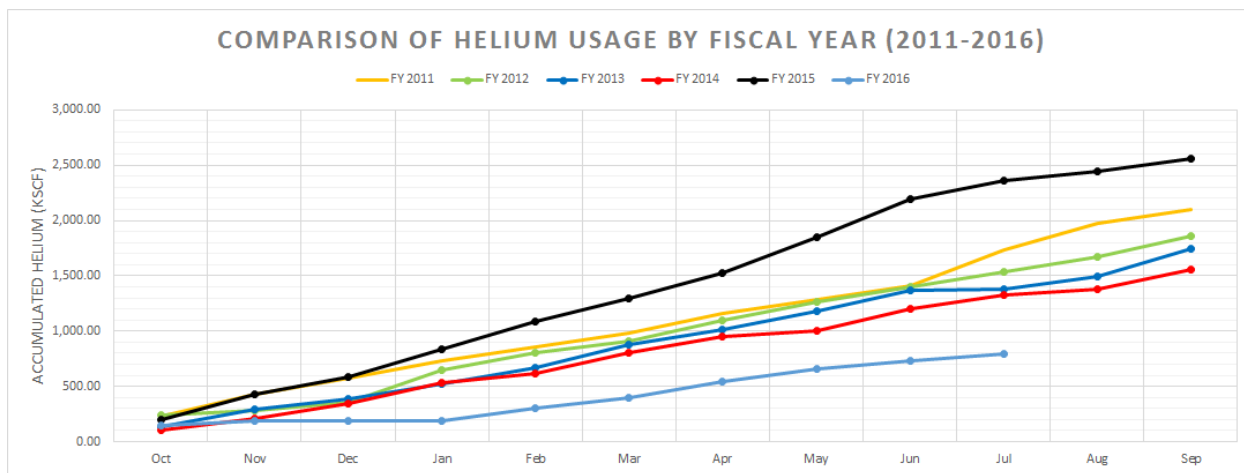


Fig. 1. Helium consumption trends for recent fiscal years

Figure 2 shows the average total use, compared with helium purchased for use, from FY08 through FY15. Fluctuations in monthly use tend to average out over the course of a year of operation; those fluctuations are typically associated with down time because of contamination or maintenance, which happen somewhat randomly through the year. Besides FY15, only FY10 was anomalously high: this was the result of high stored energy magnet testing which created high pressure gas return that could not be absorbed without tripping off the refrigerator compressors, and helium had to be vented. Subsequently the vent piping was tied in to a dedicated gas storage tank that prevents such helium loss. Table 1 summarizes the Actual Use per month from FY11 through FY16 (through July). Taking the years FY11 through FY14 to represent the recent typical monthly helium consumption, the average is 150 kscf (thousand standard cubic feet). Including FY15 and FY16 yields the same average result.

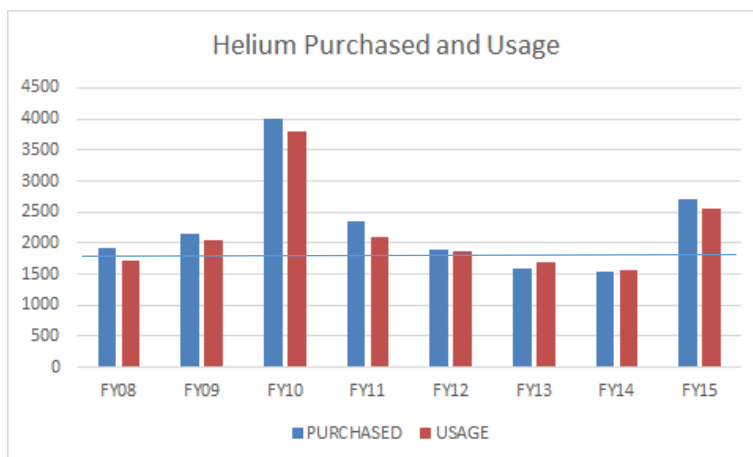


Fig. 2. Recent history of annual total IB1 helium consumption, and FY11-14 average rate line.

Table 1. Average Monthly Actual Helium Use [kscf] by Fiscal Year

Fiscal Year	Average Helium Usage/month
2011	174.67
2012	154.86
2013	145.49
2014	129.56
2015	213.31
2016	79.22
<b>Average FY11-14</b>	<b>151.15</b>
<b>Average FY11-16</b>	<b>149.52</b>

Figure 3 shows the trend for use of LN<sub>2</sub> in recent years. Starting in about 2010, N<sub>2</sub> flow sensors were introduced around the facility to study use patterns and increase efficiency; for example the helium pre-cooler use was able to be reduced. In mid FY12 a monitor was added to measure N<sub>2</sub> from IB1 used in IB2 for vacuum epoxy impregnation of magnets. IB2 use for FY13-16 is also shown in Fig. 3, and is both significant and unrelated to IB1 cryogenic systems. Figure 4 shows the IB1-only LN<sub>2</sub> usage for this period, with FY16 projection for the final 2 months. From FY13-16, the recent typical annual LN<sub>2</sub> consumption in IB1 is 39000 kscf (see Table 2), or 3250 kscf per month on average.

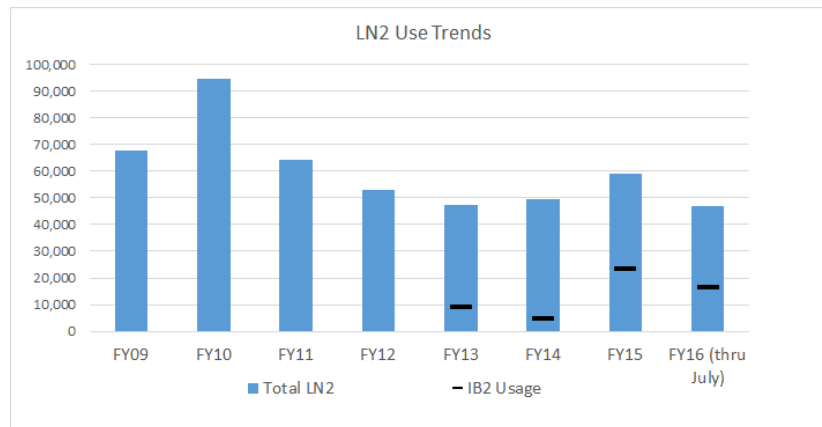


Fig. 3. Recent history of total annual IB1 LN<sub>2</sub> purchased, and recent measured IB2 use.

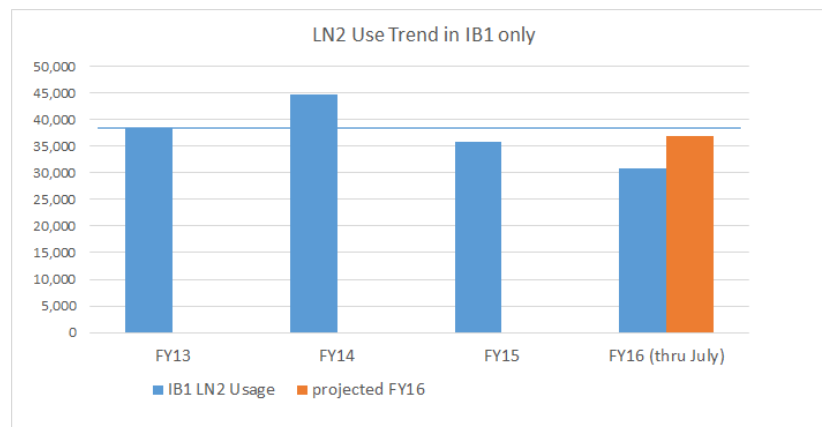


Fig. 4. Recent history of annual total IB1 LN<sub>2</sub> consumption, and FY13-16 average rate line.

Table 2. Annual LN2 use in IB1 cryogenic systems

Fiscal Year	Total LN2 Use [kscf]	IB2 LN2 Use [kscf]	IB1 only LN2 Use [kscf]
FY11	64,408.28		
FY12	53,013.48		
FY13	47,432.65	8997.2	38,435.50
FY14	49,564.04	4782.0	44,782.07
FY15	59,091.05	23258.3	35,832.74
FY16 thru July	46,945.79	16123.4	30,822.41
FY16 projected			36,986.89
<b>Average FY13-16</b>			<b>39,009.30</b>

The history of prices for helium and liquid nitrogen are shown in Figures 5 and 6 respectively; current lab-wide contracts extend through FY17 which is also shown. Helium is purchased both in gas and liquid form from different vendors. The liquid helium price is significantly lower and therefore we mostly purchase liquid helium in 500 liter dewars. Prices for cryogenics in FY16 and FY17 are shown in Table 3.

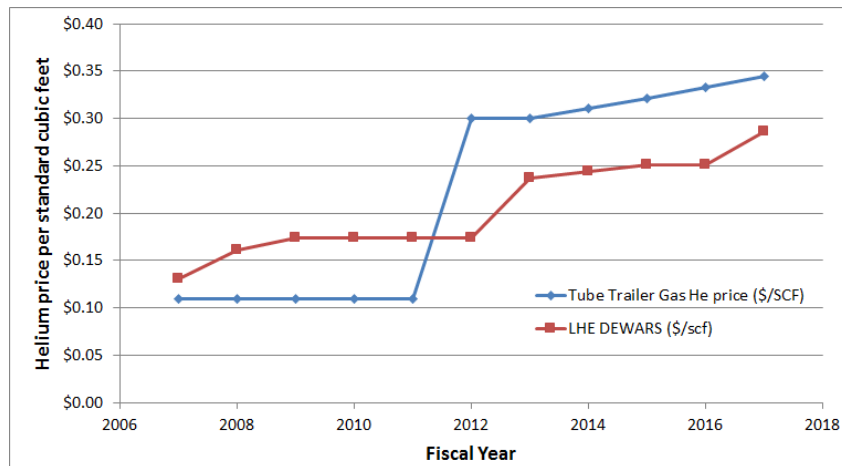


Fig. 5. Helium gas and liquid cost trends at Fermilab.

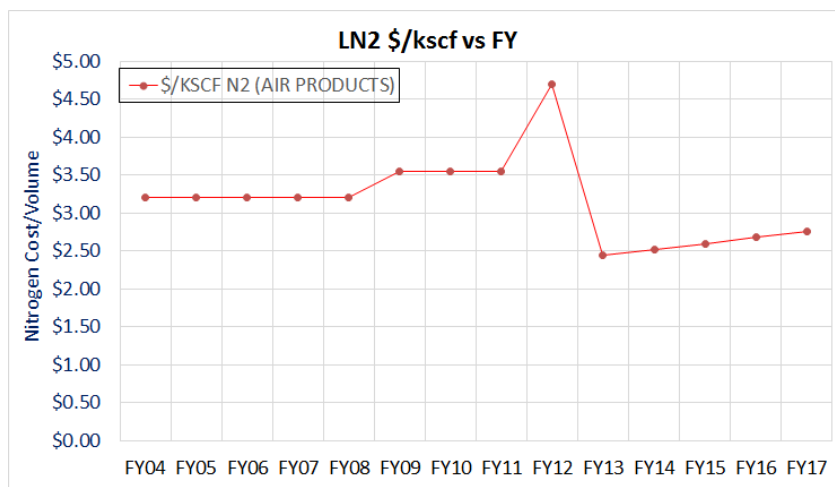


Fig. 6. Liquid Nitrogen cost trends at Fermilab.

Table 3. FY16 and FY17 cryogen prices

Fiscal Year/Cryogen [\$/kscf]	Gas Helium (Prax Air)	Liquid Helium (Linde)	Liquid Nitrogen (Air Products)
FY16	332.6	251.4	2.68
FY17	344.3	286.3	2.76

### IB1 Cryogenic Systems and Test Stands

The IB1 cryogenic test facilities date back to the Tevatron era, when the refrigeration plant and cryogen distribution systems were installed for production horizontal magnet tests. Changes to the facility were subsequently made for SSC magnet testing (circa 1990), LHC magnet testing (VMTF in 1995; Stand 4 in 2000), HTS leads and small SC magnet testing (Stand 3 in 1999), and superconducting RF testing (VTS1 in 2007; VTS2,3 in 2014).

Major improvements to refrigeration plant and test stand infrastructure were started in 2008, to increase helium liquefaction rate, sub-atmospheric pumping capability (to lower helium temperature), and “full stream” helium purification for increased reliability and reduced helium losses (actual amount to be determined). This last upgrade is now complete and is expected to begin operation early in FY17; the purifier is predicted to result in 20-25% increased LN<sub>2</sub> use.

Vertical test stands (VMTF, VTS1-3) are supplied by an over-the-roof transfer line, while horizontal test stands are supplied through a distribution box; when in use, these contribute (poorly known) heat loads that result in some inefficiency in delivering liquid helium. The VTS systems are built to allow transfer of liquid helium between stands; this makes efficient use of the liquid helium and reduces SRF cavity testing time, by allowing it to be locally stored and rapidly transferred.

The cryogenic test programs encompass R&D and production studies of magnets, current leads, RF cavities, materials, and sensors. Test stand volumes range from very small to very large, and the range of mass and dimensions of devices tested in each of the test stands also varies greatly. Cryogenic operation of the stands is diverse and dynamic (e.g., re-use at VTS), and the facility lacks (expensive & complicated) monitors to track or calculate the actual volume of helium used in each test.

Consequently we have established a method to assess cryogen use and charges that is easily understood and can be accounted for historically and in the future. It relies on two indicators that directly reflect the scale of use: time spent cold testing, and test stand volume. Since the cryogen losses are continuous, it is equitable to distribute the cost burden according to the time spent utilizing the facilities. The test stand volume represents the scale of helium use in a test: helium volume used for pump & back-fill purification cycles, the volume of liquid helium needed to cool the test stand and device mass, the volume of liquid helium used during the test (e.g., fill and maintain a liquid level, pump on volume to reach low temperature, thermal cycling devices in the cryostat) – volumes that must be re-liquified by the refrigeration plant. Table 4 summarizes the volumes of currently operating cryogenic test vessels.

Table 4. IB1 test stand cryogenic vessel volumes

Vessel	VMTF	VTS1	VTS2	VTS3	HMTF3	LTCF	MCTF
Volume [cu ft]	15100	30000	63000	63000	3000	1860	1860

The test stands and their historic or anticipated use are as follows:

VMTF: Vertical Magnet Test Facility, generally large but also small SC magnet tests

PIP-II SSR1 solenoids in FY15, SSR2 in the future; LARP model magnet program; High Field Magnet program; Mu2e planned splice-in-magnet test

VCTF: Vertical Cavity Test Facility has three cryogenically interconnected test stands

VTS1: up to 3 R&D and/or production cavities, vertically stacked

VTS2: up to 3 Production LCLS-II, PIP-II, or R&D cavities

VTS3: up to 3 Production LCLS-II, PIP-II, or R&D cavities

HMTF3: “Stand 3” small SC magnets and HTS leads

LCLS-II production magnet tests; Mu2e HTS leads qualification tests

LTCF: Low Temperature Calibration Facility, low temperature sensor calibrations

MCTF: Material Characterization Test Facility, low temperature material property studies

Test stand daily use is tracked and summarized by Test & Instrumentation department engineering staff and reported to the T&I department head on a monthly basis. Test activities are captured in the T&I electronic logbook, by entries that include date and time stamp, test stand, device under test, specific activity, and operator making the entry. This information is summarized for each test stand according to time spent in various states. Cold test time is defined as the time from start of a cool down to the start of a warm up, or start of liquid helium transfer to another VTS stand. Note that once a VTS test is complete, subsequent use of the cryostat for storing liquid helium (before warming up) is not charged to the project. Detailed test stand information (temperatures, pressures, liquid levels, valve positions, etc.) is also captured by the plant and stand controls system, and a procedure to semi-automate this accounting is under development. Table 5 illustrates the summary of test stand use for FY16 through the month of July.

Table 5. IB1 Test stand history in FY16 through July

Yearly Total Summary										
	Sub Atm (hrs)	4.5K (hrs)	80K (hrs)	100K (hrs)	Floating (hrs)	Warm Up (hrs)	Warm Up He (hrs)	Warm Up N2 (hrs)	Cooldown (hrs)	Test Cycles
VMTF	338	1,449	0	-	-	-	875	0	430	6.0
VTS-1	504	1,844	-	0	-	2,518	-	-	272	206.0
VTS-2	284	2,552	-	0	-	1,065	-	-	71	25.5
VTS-3	45	4,681	-	0	-	314	-	-	22	6.5
TS-3	0	1,457	0	-	-	188	-	-	20	4.5
MCTF	0	686	0	-	-	160	-	-	6	2.5
LTCF	0	1,241	0	-	-	329	-	-	7	3.0

Table 6 summarizes the total “cold hours” (as defined above) by test stand each month from October 2014 through July 2016. Table 7 shows the summary of cold hours weighted by test stand volume for this same period.

Table 6. Cold Hours by test stand for FY15 through July FY16

-	VMTF	VTS-1	VTS-2	VTS-3	TS-3	MCTF	LTCF
Oct-14	704	213	346	0	376	353	0
Nov-14	0	140	65	112	336	343	0
Dec-14	111	372	342	744	745	72	0
Jan-15	490	233	273	744	240	0	212
Feb-15	276	317	137	672	0	0	180
Mar-15	199	370	299	744	0	658	0
Apr-15	0	346	283	720	0	720	0
May-15	572	324	114	744	0	744	0
Jun-15	233	263	114	720	0	204	0
Jul-15	396.5	349	257	657.5	6.5	0	398
Aug-15	106	445.5	160.5	702	6	0	0
Sep-15	615	347	124	674	0	28	0
Oct-15	58	536	577	744	271	0	0
Nov-15	230	335	357	672	334	131	0
Dec-15	27	161	360	154	94	64	0
Jan-16	0	0	0	0	0	0	0
Feb-16	168	208	59	0	0	89	0
Mar-16	558	326	416	351	0	408	87
Apr-16	519	406	309	720	0	0	254
May-16	0	168	195	744	0	0	685
Jun-16	302	203	282	677	34	0	158
Jul-16	355	277	352	686	744	0	64
Aug-16	0	0	0	0	0	0	0
Sep-16	0	0	0	0	0	0	0

Table 7. Volume-weighted cold hours by test stand for FY15 through July FY16

-	VMTF	VTS-1	VTS-2	VTS-3	TS-3	MCTF	LTCF
Oct-14	10630400	6390000	21798000	0	1128000	656580	0
Nov-14	0	4200000	4095000	7056000	1008000	637980	0
Dec-14	1676100	11160000	21546000	46872000	2235000	133920	0
Jan-15	7399000	6990000	17199000	46872000	720000	0	394320
Feb-15	4167600	9510000	8631000	42336000	0	0	334800
Mar-15	3004900	11100000	18837000	46872000	0	1223880	0
Apr-15	0	10380000	17829000	45360000	0	1339200	0
May-15	8637200	9720000	7182000	46872000	0	1383840	0
Jun-15	3518300	7890000	7182000	45360000	0	379440	0
Jul-15	5987150	10470000	16191000	41422500	19500	0	740280
Aug-15	1600600	13365000	10111500	44226000	18000	0	0
Sep-15	9286500	10410000	7812000	42462000	0	52080	0
Oct-15	875800	16080000	36351000	46872000	813000	0	0
Nov-15	3473000	10050000	22491000	42336000	1002000	243660	0
Dec-15	407700	4830000	22680000	9702000	282000	119040	0
Jan-16	0	0	0	0	0	0	0
Feb-16	2536800	6240000	3717000	0	0	165540	0
Mar-16	8425800	9780000	26208000	22113000	0	758880	161820
Apr-16	7836900	12180000	19467000	45360000	0	0	472440
May-16	0	5040000	12285000	46872000	0	0	1274100
Jun-16	4560200	6090000	17766000	42651000	102000	0	293880
Jul-16	5360500	8310000	22176000	43218000	2232000	0	119040
Aug-16	0	0	0	0	0	0	0
Sep-16	0	0	0	0	0	0	0

## IB1 Model for Project Cryogen Charges

Our model for charging projects for cryogen use is to pro-rate the project according to the fraction of weighted cold hours used by the project, to the total weighted cold test stand hours provided across the entire test facility. That is to say, the cost per weighted cold test hour is equal to the average cryogen cost per month divided by the average number of total weighted cold test hours per month. Summing the weighted cold test hours for all test stands in Table 7 from Oct-14 to Jul-16, divided by 22 months, gives the average total weighted cold hours = 63472849 hours per month. From tables 1-3 the monthly cost of cryogens in FY16 is (150 kscf \* \$251.4/kscf LHe)+(3250 kscf \* \$2.68/kscf LN<sub>2</sub>)= \$46,420 per month.

Therefore the baseline FY16 cost is \$46,420/63472849 = \$0.000731 per weighted cold test hour. Assuming the same levels of consumption in FY17 at FY17 prices, the cost per hour will increase to \$0.000818. The charges per cold test hour for each test stand, for FY16 and FY17 are shown in Table 8. For comparison, Table 9 shows the rates currently charged for cryogenic testing (of SRF devices) at other facilities. Note that IB1 charges are essentially per cold test cycle and the VTS stands can all accommodate multiple devices per test cycle; projects can take advantage of this to reduce costs.

The levels of cryogen consumption will be monitored during FY17, to determine changes due to operation of the new purification system. At some point, probably middle to late FY17, a rate adjustment for observed changes in the baseline use will be discussed. Note that the baseline total facility weighted cold test hours may also vary depending on the mix of test programs, and should also be reassessed at an appropriate time. As additional test stands (stand 4) or test configurations (HTS leads conduction cooling by helium) are brought into the mix, there will be a need to establish the corresponding test stand volume.

Table 8. Cold test hour charge rates per IB1 test stand

Test Stand	VMTF	VTS-1	VTS-2	VTS-3	TS-3	MCTF	LTCF
VOLUME (cu ft)	15100	30000	63000	63000	3000	1860	1860
<b>FY16 Cost/hour</b>	\$11.04	\$21.94	\$46.07	\$46.07	\$2.19	\$1.36	\$1.36
<b>FY17 Cost/hour</b>	\$12.35	\$24.54	\$51.53	\$51.53	\$2.45	\$1.52	\$1.52
<b>FY16 Cost/24 hr day</b>	\$265.04	\$526.56	\$1,105.78	\$1,105.78	\$52.66	\$32.65	\$32.65
<b>FY17 Cost/24 hr day</b>	\$296.41	\$588.89	\$1,236.68	\$1,236.68	\$58.89	\$36.51	\$36.51

Table 9. AD Cryo Test Facility Cryogen Charge Rates in FY16

FY16 Test Facility Cryogen Charge Rate							6/8/2016
	Helium		Nitrogen			Total Cryogens	
	Annual	Daily	Monthly		Daily		
	\$	\$	scf	\$	\$	\$/day	Comments
<b>CMTF</b>	\$ 30,000	\$ 82.19	2,000,000	\$ 5,360	\$ 178.67	\$ 260.86	minimal operating statistics
<b>MDB HTS</b>	\$ 68,000	\$ 186.30	6,910,000	\$ 18,519	\$ 617.29	\$ 803.59	typically higher dynamic losses
<b>MDB STC</b>	\$ 68,000	\$ 186.30	5,710,000	\$ 15,303	\$ 510.09	\$ 696.39	typically lower dynamic losses
<b>NML</b>	\$ 50,000	\$ 136.99	5,100,000	\$ 13,668	\$ 455.60	\$ 592.59	